



# EDGEWOOD CHEMICAL BIOLOGICAL CENTER

U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND  
Aberdeen Proving Ground, MD 21010-5424

**ECBC-TR-1422**

## VAPOR PRESSURE DATA ANALYSIS AND STATISTICS

**Ann Brozena**

**RESEARCH AND TECHNOLOGY DIRECTORATE**

**Charles E. Davidson  
Avishai Ben-David**

**SCIENCE AND TECHNOLOGY CORPORATION, INC.  
Belcamp, MD 21017-1427**

**Bryan Schindler**

**LEIDOS, INC.  
Gunpowder, MD 21010-0068**

**David E. Tevault**

**JOINT RESEARCH AND DEVELOPMENT, INC.  
Belcamp, MD 21017-1552**

**December 2016**

Approved for public release; distribution unlimited.



#### Disclaimer

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorizing documents.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 h per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
1. REPORT DATE XX-12-2016		2. REPORT TYPE Final		3. DATES COVERED (From - To) Nov 2015 – Apr 2016	
4. TITLE Vapor Pressure Data Analysis and Statistics				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHORS Brozena, Ann (ECBC); Davidson, Charles E.; Ben-David, Avishai (STC); Schindler, Bryan (Leidos); and Tevault, David E. (JRAD)				5d. PROJECT NUMBER: Chemical and Biological Defense Technology Base Program	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Director, ECBC, ATTN: RDCB-DRC-P, APG, MD 21010-5424 Science and Technology Corporation, Inc. (STC), 111 Bata Boulevard, Suite C, Belcamp, MD 21017-1427 Leidos, Inc., P.O. Box 68, Gunpowder, MD 21010-0068 Joint Research and Development, Inc. (JRAD), 4694 Millennium Drive, Suite 105, Belcamp, MD 21017-1552				8. PERFORMING ORGANIZATION REPORT NUMBER  ECBC-TR-1422	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Threat Reduction Agency, 8725 John J. Kingman Road, MSC 6201, Fort Belvoir, VA 22060-6201				10. SPONSOR/MONITOR'S ACRONYM(S) DTRA	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT: This report compares several methods for expressing vapor pressure as a function of temperature (also referred to as correlation in the traditional literature) using the Antoine equation and discusses statistical analyses of the resulting correlations. Vapor pressure varies nonlinearly with temperature and is an important property of materials for applications ranging from estimates of their behavior in the environment to design of test equipment. Vapor pressure and temperature measurements over wide dynamic ranges are difficult to obtain, and prediction of vapor pressure based on limited data may be required in certain cases, necessitating reliable relationships between pressure and temperature. While the integrated form of the Clausius–Clapeyron equation has sound theoretical basis for correlating pressure and temperature, assumptions required for the temperature dependence of enthalpy may not be valid, particularly over wide temperature ranges. To correct for those approximations, a modified correlation equation may be implemented to enable accurate extrapolation. One variation of the Clausius–Clapeyron equation is the Antoine equation, which incorporates a third fit parameter to more accurately describe the nonlinearity of vapor pressure data. The current results support the use of the procedure proposed by Penski and Latour as the best method for correlating vapor pressure data.					
15. SUBJECT TERMS <div style="display: flex; justify-content: space-between;"> <div>Vapor pressure</div> <div>Antoine equation</div> <div>Statistical analysis</div> <div>Clausius–Clapeyron equation</div> </div> <div style="display: flex; justify-content: space-between;"> <div>Standard deviation</div> <div>Volatility</div> <div>Enthalpy of volatilization</div> <div>Entropy of volatilization</div> </div>					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
U	U	U	UU	42	Renu B. Rastogi (410) 436-7545

Blank

## **PREFACE**

The work described in this report was authorized under the Chemical and Biological Defense Technology Base Program. The work was started in November 2015 and completed in April 2016.

The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

This report has been approved for public release.

## **Acknowledgments**

The authors would like to salute Mr. Elwin Penski (former ECBC employee) for his pioneering work that inspired this report. We also acknowledge technical guidance provided by Dr. John Mahle (ECBC). We also extend our gratitude to Ms. Janett Stein (ECBC library) for technical assistance.

Blank

## CONTENTS

1.	INTRODUCTION .....	1
2.	VAPOR PRESSURE CORRELATIONS .....	1
3.	FITTING METHODS .....	4
4.	STATISTICAL ANALYSIS .....	7
5.	RESULTS AND DISCUSSION .....	9
5.1	1-Hexadecanol .....	10
5.2	1-Tetradecanol .....	11
5.3	DEM .....	13
5.4	VX .....	14
5.5	RVX .....	15
5.6	TDG .....	16
5.7	<i>N,N'</i> -Diisopropylcarbodiimide (DICDI) .....	17
6.	CONCLUSIONS .....	19
	LITERATURE CITED .....	21
	ACRONYMS AND ABBREVIATIONS .....	23
	APPENDIX: SCREENSHOTS OF MICROSOFT EXCEL TEMPLATE .....	25

## FIGURE

TDG data <sup>3</sup> with Antoine curve, showing its discontinuity .....	3
---	---

## TABLES

1. 1-Hexadecanol Vapor Pressure Data from Kemme and Kreps <sup>11</sup> .....	10
2. Antoine Constants (Equation 3), Standard Deviations, and <i>S</i> for 1-Hexadecanol.....	10
3. Vapor Pressures (Torr, Equation 3) Calculated at Selected Temperatures for 1-Hexadecanol Using Constants Listed in Table 2 .....	11
4. 1-Tetradecanol Vapor Pressure Data from Kemme and Kreps <sup>11</sup> .....	11
5. Antoine Constants (Equation 3), Standard Deviations, and <i>S</i> for 1-Tetradecanol.....	12
6. Vapor Pressures (Torr, Equation 3) Calculated at Selected Temperatures for 1-Tetradecanol Using Constants Listed in Table 5 .....	13
7. Antoine Constants (Equation 3), Standard Deviations, and <i>S</i> for DEM.....	13
8. Vapor Pressures (Torr, Equation 3) Calculated at Selected Temperatures for DEM Using Constants Listed in Table 7 .....	14
9. Antoine Constants (Equation 2), Standard Deviations, and <i>S</i> for VX .....	15
10. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for VX Using Constants Listed in Table 9 and Differences from Values Calculated Using the Penski Method (Excel Software).....	15
11. Antoine Constants (Equation 2), Standard Deviations, and <i>S</i> for RVX .....	16
12. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for RVX Using Constants Listed in Table 11 .....	16
13. Antoine Constants (Equation 2), Standard Deviations, and <i>S</i> for TDG.....	17
14. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for TDG Using Constants Listed in Table 13 .....	17
15. Antoine Constants (Equation 2), Standard Deviations, and <i>S</i> for DICDI.....	18
16. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for DICDI Using Constants Listed in Table 15 .....	18
17. Standard Deviations of Antoine Constants for Compounds and Data in This Report.....	19



# VAPOR PRESSURE DATA ANALYSIS AND STATISTICS

## 1. INTRODUCTION

Knowledge of the vapor pressure of materials as a function of temperature is important for a number of reasons, including prediction of their behavior when released into the environment or laboratory, design of test apparatus for developmental test equipment, and determination of route(s) of entry for toxicological assessments. Vapor pressure-versus-temperature relationships can also be used to calculate the normal boiling point, temperature-dependent enthalpy of volatilization (vaporization for liquids and sublimation for solids), volatility, and entropy of volatilization. Vapor pressure can be reported several different ways, including tables of experimental temperature and pressure pairs, smoothed pressure values calculated at selected temperatures, or correlated equations expressing vapor pressure as a function of temperature. Vapor pressure data are plotted by convention on a scale of logarithm of pressure versus reciprocal temperature to give a straight or nearly straight line plot. When data are plotted over wide ranges, the nonlinearity of the data becomes obvious, requiring a more complicated mathematical relationship (also commonly referred to as correlation in the literature) to accurately describe the data and enable interpolation and extrapolation.

The purposes of this report are to compare several different methods for correlating vapor pressure data using the Antoine equation and to discuss statistical analyses of the resulting correlations.

## 2. VAPOR PRESSURE CORRELATIONS

Many different equations can be used to express vapor pressure as a function of temperature. This report addresses the two most prevalent in the literature, the Clausius–Clapeyron and Antoine equations.<sup>1</sup>

The Clausius–Clapeyron equation has the following form:

$$\ln(P) = \mathbf{a} - \frac{\mathbf{b}}{T} \quad (1)$$

where  $P$  is vapor pressure (Pa),  $T$  is absolute temperature (K), and  $\mathbf{a}$  and  $\mathbf{b}$  are correlation constants. The derivation of this equation has a sound thermodynamic basis, but it is based on several assumptions that are not exact. These are, primarily, that heat of vaporization (the slope of the vapor pressure curve) does not vary with temperature, and also that the molar volume of the liquid is negligible compared to that of the vapor. Although the integrated form of the Clausius–Clapeyron equation is linear on a standard plot ( $\ln P$  vs  $1/T$ ), the assumption of constant enthalpy of vaporization is not valid over wide temperature ranges. As a result, this equation only accurately represents data over narrow temperature ranges.

Note: Throughout this report, Antoine and Clausius–Clapeyron equation correlation constants are shown in bold for clarity.

The modified integrated Clausius–Clapeyron and other empirical relations have been developed to better describe vapor pressure data. One of these modifications is the Antoine equation (eq 2, for Kelvin and Pascal units; eq 3 for Celsius and Torr units), which is easy to solve, less cumbersome than higher-term equations, takes into account the variation in heat of vaporization with temperature, and accurately describes data over broad experimental ranges, thereby enabling interpolation and limited extrapolation of the data.

$$\ln(P) = \mathbf{a} - \frac{\mathbf{b}}{(\mathbf{c} + T)} \quad (2)$$

where  $P$  is vapor pressure (Pa);  $T$  is absolute temperature (K);  $\mathbf{a}$ ,  $\mathbf{b}$ , and  $\mathbf{c}$  are correlation constants; and  $\ln$  denotes the natural logarithm. The  $\mathbf{c}$  value is usually negative, reflecting the negative curvature of the vapor pressure plot and decreasing enthalpy of vaporization as temperature increases.

$$\log(p) = \mathbf{A} - \frac{\mathbf{B}}{(\mathbf{C} + t)} \quad (3)$$

where  $p$  is vapor pressure (Torr);  $t$  is Celsius temperature;  $\mathbf{A}$ ,  $\mathbf{B}$ , and  $\mathbf{C}$  are correlation constants; and  $\log$  denotes logarithm in base 10. For these units, a  $\mathbf{C}$  value less than 273.15 reflects the slight negative curvature typically observed for vapor pressure data over a large temperature range.

Although other combinations of units are found in the literature for the Antoine equation, the current discussion is limited to the two listed above, which can be interconverted to express pressure and temperature as Pascal and Kelvin (eq 2) or Torr and Celsius (eq 3) using eqs 4–6. The units used here conform with those used in the original reports.

$$\mathbf{a} = \mathbf{A} \cdot \ln(10) + \ln(101325/760) \quad (4)$$

$$\mathbf{b} = \mathbf{B} \cdot \ln(10) \quad (5)$$

$$\mathbf{c} = \mathbf{C} - 273.15 \quad (6)$$

The advantages and disadvantages of the Antoine equation have been summarized by Penski.<sup>2</sup> An additional disadvantage of the Antoine equation is that the predicted pressure is incorrect at temperatures far below the experimental temperature limit; the calculated vapor pressure becomes undefined when the denominator approaches zero, such as when the absolute value of the (negative)  $\mathbf{c}$  constant is equal to the experimental temperature. This anomaly makes it inappropriate to extrapolate significantly below the low-temperature limit of the data. An example of this effect is illustrated by the Antoine equation for thiodiglycol (TDG)<sup>3</sup> in the figure. That said, since absolute values of  $\mathbf{c}$  are usually less than 100, this deficiency of the Antoine model is often of academic interest only. A quantitative assessment of the extrapolation accuracy to lower temperatures has not been fully investigated.

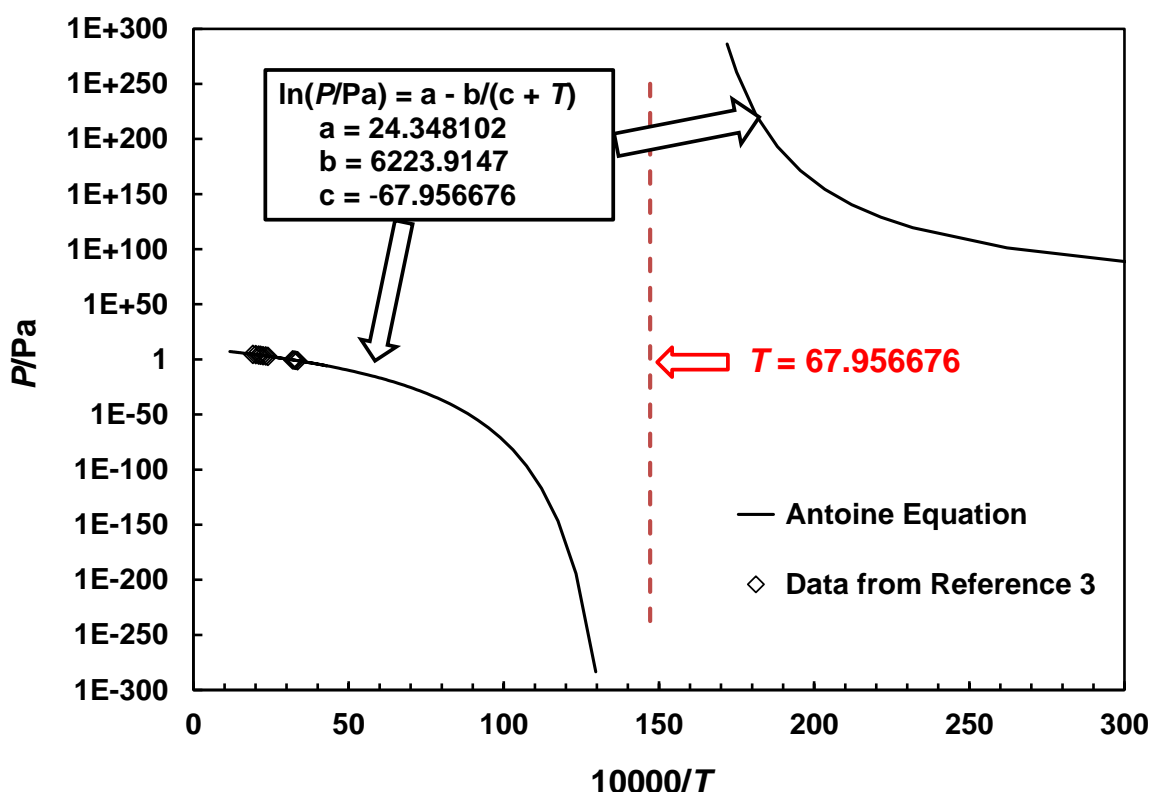


Figure. TDG data<sup>3</sup> with Antoine curve, showing its discontinuity.

After the **a**, **b**, and **c** constants are fit to the vapor pressure data, it may be asked whether **a**, **b**, and **c** are meaningful fit parameters. Judging the quality of the fit by observing the residual (data model) provides only a partial answer. However, using **a**, **b**, and **c** to estimate other physical parameters will provide the user with a feel for the quality of **a**, **b**, and **c**. We consider four ways to address this aim.

1. Assessment of the expected order of magnitude of **a**, **b**, and **c**. Equation 2 (K and Pa) usually results in **a**, **b**, and **c** constants of approximately 24, 5000, and -70, respectively. Equation 3 (°C and Torr) normally has **A**, **B**, and **C** constants near 8, 2000, and 200, respectively. The **A** (or **a**) value is directly related to vapor pressure and will be greater for high vapor pressure materials.
2. Prediction of the normal boiling temperature and comparison to the experimentally determined normal boiling point temperature.
3. Estimation of the enthalpy of vaporization as a function of  $T$  from the Antoine equation coefficients as follows. Although the basis of the Antoine equation is partially empirical, the temperature-dependent enthalpy of vaporization may be calculated by first taking the derivative of eq 2 with respect to temperature (eq 7) and then multiplying by  $RT^2$ , as shown in eq 8,

$$\frac{d \ln(P)}{dT} = \frac{\mathbf{b}}{(\mathbf{c} + T)^2} \quad (7)$$

$$\Delta H_{\text{vap}} = \frac{d \ln(P)}{dT} \cdot RT^2 = \mathbf{bR} \cdot \frac{T^2}{(\mathbf{c} + T)^2} \quad (8)$$

where  $\Delta H_{\text{vap}}$  is enthalpy of vaporization (or enthalpy of sublimation for solids). Over narrow temperature ranges,  $\mathbf{c}$  is often neglected, eq 8 reduces to eq 9, and the calculated enthalpy of vaporization does not depend on temperature.

$$\Delta H_{\text{vap}} = \mathbf{bR} \quad (9)$$

4. Calculation of the entropy of vaporization, which is defined as the enthalpy of vaporization at the normal boiling point divided by the normal boiling point temperature. Trouton's rule states that this value should be approximately 89 J/mol-K, although deviations to higher values due to hydrogen bonding may be expected.

Using the model fit parameters to identify potentially flawed experimental data can be instructive. An example is provided by TDG; its vapor pressure was first reported by Bauer and Burschkies<sup>4</sup> in 1935 without a correlation equation. The  $\mathbf{a}$  and  $\mathbf{b}$  correlation constants for the Clausius–Clapeyron equation based on their data are unusually low, the extrapolated normal boiling point of greater than 1300 K is unreasonably high, and the calculated enthalpy of vaporization of less than 20 kJ/mole is extraordinarily low, suggesting problems with the data. New data published in 2014 by Brozena et al.<sup>3</sup> suggested a more realistic normal boiling point (553 K) and standard enthalpy of vaporization (86.8 kJ/mole) and are in good agreement with recent manufacturers' data. In addition, values for the constants and derived thermodynamic properties are in the expected ranges. Numerical analysis would have suggested that there were flaws in the original data prior to its publication.

### 3. FITTING METHODS

Our process for correlating experimental vapor pressure data to either the Antoine or Clausius–Clapeyron equation has evolved over time with updates, as required, based on the computer technology available and our understanding of the options for fit optimization. Several different but related methods are addressed in this report. All of these methods are based on least-squares solutions; the Clausius–Clapeyron equation is linear when plotted on a standard vapor pressure plot of  $\ln(P)$  versus  $T^{-1}$ , whereas the Antoine equation is nonlinear with negative curvature on such a plot.

Unless otherwise stated, the metric used to optimize the fits described in this report is least-squares error applied to the logarithm of pressure, which is the sum of the squares

of the differences between the logarithms of experimental and calculated values, referred to by Penski<sup>2</sup> and in this report as  $S$ :

$$S = \sum_{i=1,n} (Y_i - \mathbf{a} - \mathbf{b}X_i)^2 \quad (10)$$

where  $n$  is the number of data points,  $Y_i$  is the natural logarithm of the  $i^{\text{th}}$  experimental vapor pressure value, and  $X_i$  is the negative reciprocal of the sum of the  $\mathbf{c}$  constant and the  $i^{\text{th}}$  experimental temperature value. For *O*-ethyl *S*-(2-diisopropylaminoethyl) methyl phosphonothiolate and *O*-isobutyl-*S*-[2(diethylamino)ethyl] methylphosphonothiolate (VX and RVX, respectively), the sum of the absolute values of the percent differences between the experimental and calculated values was used as the metric.

In 1971, Penski and Latour developed and described in detail<sup>5</sup> a Fortran program to find values for  $\mathbf{A}$ ,  $\mathbf{B}$ , and  $\mathbf{C}$  that minimize  $S$ , which is a nonlinear regression problem and therefore requires an iterative solution procedure. The problem is nonlinear because of the  $\mathbf{C}$  coefficient;  $\mathbf{A}$  and  $\mathbf{B}$  appear linear if the value of  $\mathbf{C}$  is known. Penski and Latour's method takes advantage of this conditional linearity by performing a one-dimensional golden section search to find the optimal value of  $\mathbf{C}$  given a reasonable starting value. At each iteration, the optimal  $\mathbf{A}$  and  $\mathbf{B}$  values given the current value of  $\mathbf{C}$  are easily found as a solution to a linear least-squares problem. This method was updated in 1989 by Dr. Kenneth Collins (U.S. Army Edgewood Chemical Biological Center [ECBC]) to a Basic program, enabling the fit to be performed using a desktop computer.<sup>2</sup>

In 1992, Penski updated his method<sup>2</sup> to address a number of deficiencies, including the lack of statistical analysis of the least-squares fitting. This update included equations to estimate the standard errors of the  $\mathbf{A}$  and  $\mathbf{B}$  Antoine coefficients; however, Penski treated the solution value of  $\mathbf{C}$  as if it were exact. In reality, because  $\mathbf{C}$  is determined from the data, it is also subject to error; and the error in  $\mathbf{C}$  also must be propagated to  $\mathbf{A}$  and  $\mathbf{B}$ . As a result of this oversight, the standard errors of  $\mathbf{A}$  and  $\mathbf{B}$  as estimated by Penski's equations are too small. For example, Penski's  $\sigma_{\mathbf{A}}$  and  $\sigma_{\mathbf{B}}$  values for diethyl malonate (DEM) in Appendix I of reference 2 are 0.020955 and 3.200, respectively, compared to our values, 0.0573171 and 33.9768. In the following discussion, we correct the statistical analysis of the Antoine equation and provide more accurate equations for estimating the scatter in the data used to determine the Antoine fit, using standard nonlinear regression theory.<sup>6</sup> Penski also pointed out that the correlations presented in 1971 were determined using low-precision calculations, and that higher-precision calculations produced better fits to the experimental data, as determined by the  $S$  values.

In the late 1990s, we recognized the need to update our vapor pressure correlation capabilities to something more flexible with wider availability than Penski's Fortran program. A Microsoft Excel spreadsheet using the Solver program was developed in-house and appeared to have the desired capability. This approach, which was also based on a least-squares optimization scheme, relies on minimizing  $S$  (eq 10). One drawback of this method was the requirement to provide reasonable starting estimates of the correlation constants in order for the Solver program to find the optimum solution.

Several modifications of the Excel spreadsheet have been explored. In an attempt to optimize the correlation of data sets including outliers, an alternate metric was employed,

minimizing the sum of the absolute values of the percent differences between the experimental and calculated values,  $D$ , a metric that appears to minimize the influence of experimental outliers on the overall fit.<sup>7</sup>

Another modification of the basic Excel Solver procedure, identified herein as the “**b** optimization method”, is performed by varying the **b** constant and allowing Solver to determine values of **a** and **c** that minimize  $S$ . This method of deriving Antoine equation coefficients from experimental data by optimization of the **b** constant is tedious in that it requires manual variation of **b** for each iteration. In some instances, the coefficients produced by this method were found to depend on the starting values selected for the **a** and **c** constants, thereby yielding unoptimized “solutions”. These unreliable solutions can be identified most easily by graphing  $S$  versus **b** in real time to determine which points do not lie on a smooth curve and, therefore, should be disregarded. This unpredictable reliability, especially the dependence of the solution on the initial values of the **a** and **c** constants, caused us to search for an alternative method that combined the robustness of Penski’s original and updated methods with the availability and flexibility of Excel software.

Recently we adapted Penski’s method to make it compatible with Excel software using Solver and the  $S$  metric. This method has the advantage of not requiring operator intervention to arrive at the optimum solution. Although we found a few examples in which Penski’s method could not optimize the correlation due to the selection of the **c** constant starting value, those cases appear to be rare and easily identifiable.

The Penski method (using Excel software) is described as follows:

- Enter the total number of data points ( $n$ ) representing the experimental data pairs (vapor pressure and temperature) into separate columns in the Excel (or similar) worksheet.
- Using eqs 8 and 9 in Penski and Latour’s report,<sup>5</sup> calculate  $X_i$ ,  $Y_i$ ,  $X_i^2$ ,  $Y_i^2$ ,  $X_iY_i$ , and their sums.
- Calculate the Antoine **b** constant using eq 11 in reference 5 with the total number of data points and sums of  $X_i$ ,  $Y_i$ ,  $X_i^2$ , and  $X_iY_i$  values; where  $X_i$  equals  $-1/(c + T)$ ,  $Y_i$  equals  $\ln(P_i)$ , and  $S$  equals the sum of the squares of the differences of the natural logarithms of experimental and correlated vapor pressure values, as described in Penski and Latour’s report.<sup>5</sup>
- Calculate the Antoine **a** constant using eq 10 in reference 5 with the Antoine **b** constant from the previous step, the total number of data points, and the sums of the  $X_i$  and  $Y_i$  values.
- Compute  $S$  according to eq 10 in this report using the total number of data points; the sums of  $X_i$ ,  $Y_i$ ,  $X_i^2$ ,  $Y_i^2$ , and  $X_iY_i$  values; and the Antoine **a** and **b** constants from above.
- Using the Excel Solver program, find the value of **c** that minimizes  $S$ . This step also generates solution values for **a** and **b**.

This method may be used to analyze data generated using other units; however, the fit determined using one unit system will only correspond to that using the same data in another unit system if unrounded values are used for the converted experimental values.

#### 4. STATISTICAL ANALYSIS

The fitting of Antoine coefficients to measured (temperature–pressure) data is a problem of nonlinear least squares, which requires an iterative solver. As mentioned above, Penski and Latour noticed that the problem was linearly separable in the sense that the **a** and **b** coefficients associated with a given value of **c** can be found through linear least squares. They replaced a three-dimensional nonlinear least-squares problem (for **a**, **b**, and **c**) with a simpler one-dimensional nonlinear problem (for **c**). In Penski and Latour’s method, given an initial value for **c**, the corresponding (**a**, **b**) parameters that minimize  $S$  conditional to the assumed **c** value are found through linear least squares, and a golden section search on **c** improves the solution until convergence to a **c** value that minimizes  $S$ . Despite the fact that a one-dimensional search is used to identify **c**, fitting the Antoine equation is fundamentally a three-dimensional problem, and the estimated **a**, **b**, and **c** coefficients are each subject to error. Penski<sup>2</sup> treated the solution for **c** as if it were the true value and instead used ordinary linear least-squares error analysis to provide standard deviations of **a** and **b** conditional to **c**. This procedure fails to account for the fact that all three Antoine coefficients are estimated from the data; it underestimates the errors in **a** and **b**, and since no error estimate of **c** is provided (it is implicitly assumed to be zero), the error in **c** is underestimated as well. Here, we provide more accurate error expressions for the Antoine coefficients by applying the results of Seber’s<sup>6</sup> Theorem 2.1 to the Antoine equation.

We write the Antoine equation as  $\ln(P_i) = \mathbf{a} - \mathbf{b}/(T_i + \mathbf{c}) + \varepsilon_i$ , for  $i = 1, 2, \dots, n$ , where  $\varepsilon_i$  captures experimental error in  $\ln(P_i)$ . We assume that  $T_i$ , the temperature at the  $i^{\text{th}}$  experimental data point, is error-free. The pressures  $P_i$  are measured quantities obtained using the experimental methods described elsewhere;<sup>8–10</sup> it is reasonable to assume that their errors are normally distributed. However, in a typical experiment, the measured pressures span multiple orders of magnitude of the pressure with *relative* errors that tend to be nearly constant. Least-squares minimization with respect to pressure would improperly weight higher pressure (higher temperature) values. Minimizing the sum-of-square residuals of the logarithm of  $P_i$  ( $S$ ) removes the effect of magnitude, and the logarithm converts constant relative error in  $P_i$  to constant absolute error in  $\ln(P_i)$  ( $d \ln(P)/dP = dP/P$ ). Thus, minimization of  $S$  is an ordinary (unweighted) least-squares problem. The error analysis of least-squares problems is facilitated by an assumption that the errors are normally distributed. As mentioned above, we assumed normally distributed errors for  $P$ ; thus,  $\ln(P)$  is not technically normally distributed. However, a Taylor expansion of  $\ln(P)$  can be used to establish that if  $P$  is normally distributed, then  $\ln(P)$  is also very closely normally distributed, as long as the relative error in  $P$  is less than approximately 10%. Typical relative errors in our experiments are generally less than 3%.

For notational convenience in the following discussion, we let  **$\theta$**  (bold type indicates a vector or matrix quantity) be the three-dimensional column vector of Antoine coefficients,  $\mathbf{\theta} = (\mathbf{a}, \mathbf{b}, \mathbf{c})^T$ , where superscript T denotes the transpose operator. We also use **P** and **T** to denote the  $n$ -element column vectors whose  $i^{\text{th}}$  elements are  $P_i$  and  $T_i$ , respectively.

The error analysis of a nonlinear regression problem hinges on a first-order Taylor expansion of the model equation around the solution value. As long as the model equation is sufficiently linear in a region around the true solution, asymptotic results from standard linear least squares apply. For our purpose, it is most important that the least-squares solution value  $\boldsymbol{\theta}$  is normally distributed, unbiased, and has a covariance matrix given by  $\sigma^2 \boldsymbol{\Sigma}^{-1}$ , where superscript  $-1$  denotes the matrix inverse, and  $\sigma^2$  is the variance of  $\ln(P)$  around the model fit. The matrix  $\boldsymbol{\Sigma}$  is given by

$$\left( \frac{\partial \ln \mathbf{P}}{\partial \boldsymbol{\theta}^T} \right)^T \left( \frac{\partial \ln \mathbf{P}}{\partial \boldsymbol{\theta}^T} \right)$$

where  $\frac{\partial \ln \mathbf{P}}{\partial \boldsymbol{\theta}^T}$  is the  $n$ -by-3 matrix of first derivatives of the model equation with respect to the coefficients. The  $i^{\text{th}}$  row of the first derivative matrix is given by

$$\frac{\partial \ln P_i}{\partial \boldsymbol{\theta}^T} = \left( \frac{\partial \ln P_i}{\partial \mathbf{a}} \quad \frac{\partial \ln P_i}{\partial \mathbf{b}} \quad \frac{\partial \ln P_i}{\partial \mathbf{c}} \right) = \left( 1 \quad -\frac{1}{T_i + \mathbf{c}} \quad \frac{\mathbf{b}}{(T_i + \mathbf{c})^2} \right)$$

The first derivative matrix may also be written as

$$\frac{\partial \ln P}{\partial \boldsymbol{\theta}^T} = \left( \frac{\partial \ln P}{\partial \mathbf{a}} \quad \frac{\partial \ln P}{\partial \mathbf{b}} \quad \frac{\partial \ln P}{\partial \mathbf{c}} \right) = \left( \mathbf{1} \quad -\frac{1}{T + \mathbf{c}} \quad \frac{\mathbf{b}}{(T + \mathbf{c})^2} \right)$$

where  $\mathbf{1}$  is the  $n$ -element vector whose elements all equal 1, and all mathematical operations are understood to be element-by-element (for instance,  $1/T$  would indicate the vector consisting of reciprocals of the elements of the  $n$ -element vector  $\mathbf{T}$ ). The elements of the matrix  $\boldsymbol{\Sigma}$  are given here explicitly:

$$\boldsymbol{\Sigma} = \begin{pmatrix} n & -\sum_{i=1}^n (T_i + \mathbf{c})^{-1} & \mathbf{b} \sum_{i=1}^n (T_i + \mathbf{c})^{-2} \\ -\sum_{i=1}^n (T_i + \mathbf{c})^{-1} & \sum_{i=1}^n (T_i + \mathbf{c})^{-2} & -\mathbf{b} \sum_{i=1}^n (T_i + \mathbf{c})^{-3} \\ \mathbf{b} \sum_{i=1}^n (T_i + \mathbf{c})^{-2} & -\mathbf{b} \sum_{i=1}^n (T_i + \mathbf{c})^{-3} & \mathbf{b}^2 \sum_{i=1}^n (T_i + \mathbf{c})^{-4} \end{pmatrix}$$

Note that the matrix  $\boldsymbol{\Sigma}$  is symmetric and involves only six unique quantities (corresponding to either the upper or lower triangular portion of the matrix).

Although  $\sigma^2$  may not be known *a priori*, an estimate is given by  $\hat{\sigma}^2 = S/(n-3)$ , where  $n-3$  is the number of degrees of freedom for  $n$  data points minus the three variables,  $\mathbf{a}$ ,  $\mathbf{b}$ , and  $\mathbf{c}$ ; therefore, the standard errors of the Antoine coefficients may be estimated by the square roots of the diagonal elements of  $\hat{\sigma}^2 \boldsymbol{\Sigma}^{-1}$ . It should be noted that the covariance matrix  $\hat{\sigma}^2 \boldsymbol{\Sigma}^{-1}$  is in



general *not* a diagonal matrix, and that the **a**, **b**, and **c** parameters can be highly correlated. This is reflective of the fact that if one of the parameter values is changed from the optimum value, the other two can compensate, reducing the increase in the  $S$  value.

We caution the reader that the high correlation of the error in **a**, **b**, and **c** must be kept in mind because it impacts the calculation of confidence intervals. One common simple technique that might be tempting to visualize approximate confidence intervals would be to plot the model curve corresponding to  $(\mathbf{a} \pm k\sigma_{\mathbf{a}}, \mathbf{b}, \mathbf{c})$ ,  $(\mathbf{a}, \mathbf{b} \pm k\sigma_{\mathbf{b}}, \mathbf{c})$ , and  $(\mathbf{a}, \mathbf{b}, \mathbf{c} \pm k\sigma_{\mathbf{c}})$ , where  $k$  is some factor intended to achieve a certain quantile of a normal distribution. This corresponds to visualizing the model when each of the parameters is perturbed in turn (with the two other parameters remaining at their solution values). This technique should be strongly *discouraged* because it ignores the correlation between the parameters (it does not allow for the other parameters to be modified to compensate for a change in the parameter being perturbed), and therefore, it will be misleading, showing errors that will be too large. Methods for estimating approximate confidence intervals for nonlinear regression problems are discussed in detail elsewhere.<sup>6</sup> In general, if the problem is sufficiently linear around the solution value, then confidence intervals from linear regression theory are appropriate.

The calculations for the standard deviations are summarized as follows:

- Calculate  $\sum_{i=1}^n (T_i + \mathbf{c})^{-2}$ ,  $\sum_{i=1}^n (T_i + \mathbf{c})^{-3}$ , and  $\sum_{i=1}^n (T_i + \mathbf{c})^{-4}$ ;
- Calculate  $\hat{\sigma}^2 = S/(n - 3)$ ;
- Construct the matrix  $\Sigma$  and its inverse  $\Sigma^{-1}$ ; and
- Calculate standard deviations of **a**, **b**, and **c** Antoine equation constants using  $\hat{\sigma}^2$  and diagonals of inverted matrix,  $\sigma_{\mathbf{a}} = (\hat{\sigma}^2 \Sigma^{-1}[1,1])^{1/2}$ ;  
 $\sigma_{\mathbf{b}} = (\hat{\sigma}^2 \Sigma^{-1}[2,2])^{1/2}$ ; and  $\sigma_{\mathbf{c}} = (\hat{\sigma}^2 \Sigma^{-1}[3,3])^{1/2}$ , where the notation  $\Sigma^{-1}[i,i]$  refers to the  $i^{\text{th}}$  diagonal element of the matrix  $\Sigma^{-1}$ .

## 5. RESULTS AND DISCUSSION

Two data sets analyzed by Penski and Latour<sup>5</sup> and one set by Penski<sup>2</sup> were used in this work to demonstrate how the more recent correlation approaches (the Excel version of Penski's method and **b** optimization) compare to the results obtained using the earlier methods. Those are discussed here in detail. Four other examples contained in recent publications from our laboratory were examined using Penski's method (Excel software) and are compared to the published results, which were determined using the **b** optimization method. The published Antoine constants for VX and RVX were derived using a different metric, as described in Sections 5.4 and 5.5, respectively.

## 5.1 1-Hexadecanol

The data listed in Penski and Latour's 1971 technical report<sup>5</sup> for 1-hexadecanol (Chemical Abstracts Service [CAS] no. 36653-82-4), which were originally published by Kemme and Kreps,<sup>11</sup> are listed in Table 1.

Table 1. 1-Hexadecanol Vapor Pressure Data from Kemme and Kreps<sup>11</sup>

Temperature (°C)	Vapor Pressure (Torr)
172.1	5.9
185.3	10.3
193.4	15.1
201.0	19.8
211.0	30.1
218.6	40.4
227.3	55.3
238.7	80.3
251.6	120.3
269.3	200.5
285.0	302.1
305.9	502.4
325.1	759.2

Repeating these calculations using the Penski method (Excel software) produced a similar, but not identical, result. The **b** optimization method also produced similar results that were more like the Penski method (Excel software) than the original correlation reported by Penski and Latour.<sup>5</sup> Results obtained using these methods and Penski and Latour's earlier results are listed in Table 2. The Penski method (Excel software) gave the smallest *S* value, but that value was only marginally lower than the value derived using the **b** optimization method. The original fit reported by Penski and Latour returned a higher *S* value than the other two methods, presumably due to those authors' use of single-precision calculations in the original work.<sup>2</sup> Standard deviations of the fit constants calculated using the procedures from above are also listed in Table 2. Differences in solution values for the different methods are small fractions of the standard deviations, indicating that all methods found essentially the same solution. These results illustrate that the **b** optimization method is capable of finding high-quality fits, as in this case, although more generally its reliability can be unpredictable.

Table 2. Antoine Constants (Equation 3), Standard Deviations, and *S* for 1-Hexadecanol

Method	A	B	C	<i>S</i>
Penski and Latour <sup>5</sup>	7.06077	1893.76	128.406	0.0006029515572
<b>b</b> Optimization	7.0605568	1893.60	128.39063	0.0006029512786
Penski method (Excel software)	7.0605418	1893.5891	128.38958	0.0006029512781
Standard deviation ( $\sigma$ )*	0.1510558	110.7127	10.59318	NA

\*From Penski method (Excel software).

NA, not applicable.

These constants produced very similar calculated values, several of which are listed in Table 3 with five significant digits to illustrate the minor differences at the lower temperatures.

Table 3. Vapor Pressures (Torr, Equation 3) Calculated at Selected Temperatures for 1-Hexadecanol Using Constants Listed in Table 2

Temperature (°C)	Penski and Latour <sup>5</sup>	<b>b</b> Optimization Method	Penski Method (Excel Software)
-40	$4.3611 \times 10^{-15}$	$4.3398 \times 10^{-15}$	$4.3384 \times 10^{-15}$
0	$2.0538 \times 10^{-8}$	$2.0503 \times 10^{-8}$	$2.0501 \times 10^{-8}$
25	$5.2001 \times 10^{-6}$	$5.1952 \times 10^{-6}$	$5.1949 \times 10^{-6}$
50	0.00027918	0.00027903	0.00027902
100	0.058826	0.058816	0.058816
150	1.8139	1.8139	1.8139
200	19.690	19.690	19.690

## 5.2 1-Tetradecanol

The data listed in Penski and Latour's report<sup>5</sup> for 1-tetradecanol (CAS no. 112-72-1), which were originally published by Kemme and Kreps,<sup>11</sup> are reproduced in Table 4.

Table 4. 1-Tetradecanol Vapor Pressure Data from Kemme and Kreps<sup>11</sup>

Temperature (°C)	Vapor Pressure (Torr)
151.6	5.2
163.0	10.5
171.0	15.3
177.0	19.9
188.4	32.1
199.1	48.4
213.3	80.1
225.7	120.0
243.1	202.8
257.8	302.6
277.9	501.2
295.9	755.2

Penski and Latour's correlation published in 1971<sup>5</sup> is provided in Table 5 along with recalculations using the Penski method (Excel software) and **b** optimization methods. More significant figures were employed in the calculation, as suggested by Penski in his 1992 follow-on report.<sup>2</sup> Table 5 also lists the standard deviations of the Antoine equation constants determined from the Penski method (Excel software) analysis. As with 1-hexadecanol, the original Penski and Latour fit for 1-tetradecanol returned a higher *S* value, presumably due to the limited number of significant digits used in the calculation.

Although there were small differences in the constants, the Penski method (Excel software) yielded the same  $S$  value as **b** optimization to 10 significant figures as shown in Table 5 and nearly the same calculated vapor pressure values, listed in Table 6. It should be noted that the differences in the values calculated using the constants of Penski and Latour's method compared to those calculated using **b** optimization are well within our current experimental error limits.

Table 5. Antoine Constants (Equation 3), Standard Deviations, and  $S$  for 1-Tetradecanol

Method	A	B	C	S
Penski and Latour	6.21961	1244.90	75.5994	0.001484169359
<b>b</b> Optimization	6.2194464	1244.80	75.588371	0.001484166674
Penski method (Excel software)	6.2194449	1244.7991	75.588274	0.001484166674
Standard deviation ( $\sigma$ )*	0.1822121	104.8499	11.900099	NA

\*From Penski method (Excel software).

Table 6 provides a list of vapor pressures calculated to five significant digits at selected temperatures for 1-tetradecanol using the constants from Table 5. The extremely low calculated values in the first row of Table 6 resulted from the low value of the denominator of the Antoine correlation as the absolute value of the temperature approached the **C** constant value, as illustrated in the Figure. These anomalously low values are well beyond the limits of confident extrapolation. This result is not surprising, given that the lowest experimental data point was about 190 °C higher than the -40 °C extrapolated value and was likely the direct result of the denominator in the **B** term of the Antoine equation approaching zero. This result clearly demonstrates the danger associated with extrapolating below the experimental range using the Antoine equation. The quantitative aspects of this anomaly have not been explored.

Interestingly, the values calculated for 1-hexadecanol at -40, 0, 25, and 50 °C are higher than those for 1-tetradecanol. In fact, the vapor pressures calculated for 1-hexadecanol are higher than those for 1-tetradecanol at temperatures between -75 and +60 °C. We believe that these values are artifacts of the 1-tetradecanol Antoine equation, given that the lighter alcohol is unlikely to have lower vapor pressure than the heavier alcohol at any temperature. It appears to us that there is a transcription error in the lowest point of the 1-tetradecanol data reported by Kemme and Kreps,<sup>11</sup> which probably should have been 5.7 instead of 5.2 Torr. The lower value caused Penski and Latour's 1971 fit<sup>5</sup> to have greater curvature, characterized by a smaller **C** value, than would have been found using the correct data value. The strongest evidence for a transcription error is that changing the lowest value to 5.7 Torr produces the same average and maximum errors listed in the original report.<sup>11</sup> The only relevance to the current discussion is that the low **C** value calculated by Penski and Latour brings into question the accuracy of the original data. Changing the lowest value in the original report to 5.7 Torr increases the **C** value to a more reasonable value, near 100, but still leaves doubt about the accuracy of the data set because the **C** value is still lower than what is usually found.

Table 6. Vapor Pressures (Torr, Equation 3) Calculated at Selected Temperatures for 1-Tetradecanol Using Constants Listed in Table 5

Temperature (°C)	Penski and Latour <sup>5</sup>	<b>b</b> Optimization Method	Penski Method (Excel Software)
-40	$1.7779 \times 10^{-29}$	$1.7447 \times 10^{-29}$	$1.7444 \times 10^{-29}$
0	$5.6565 \times 10^{-11}$	$5.6403 \times 10^{-11}$	$5.6402 \times 10^{-11}$
25	$6.9950 \times 10^{-7}$	$6.9865 \times 10^{-7}$	$6.9864 \times 10^{-7}$
50	0.00020321	0.00020310	0.00020309
100	0.13495	0.13494	0.13494
150	5.0283	5.0284	5.0284
200	50.414	50.416	50.416

### 5.3 DEM

The data listed in Penski's 1992 technical report for DEM (CAS no. 105-53-3) were measured by Brozena et al. and reported in a recent journal article.<sup>12</sup> The constants calculated by Penski in 1992 match those calculated using the Penski method (Excel software) to within 1 part per million, as shown in Table 7. It should be noted that all three methods yielded the same *S* values to nearly 10 significant digits. It is possible that small differences were due to rounding of the constants in Penski's report to eight digits, and those differences could be indicative of tighter stopping tolerances in the Excel Solver software. In either case, the differences are of little practical importance. Table 7 also lists the standard deviations of the Antoine equation constants determined from the Penski method (Excel software) analysis.

The differences observed for the constants in reference 12 are due to selection of different data points for that analysis. Differential thermal analysis (DTA) data points at pressures below 650 Pa were not used for the **b** optimization calculation in the more recent report due to the large uncertainties in those data.

Table 7. Antoine Constants (Equation 3), Standard Deviations, and *S* for DEM

Method	<b>A</b>	<b>B</b>	<b>C</b>	<i>S</i>
Penski <sup>2</sup>	8.0005804	2146.40052	223.081	0.02112108143
<b>b</b> Optimization (this work)	8.0005812	2146.401	223.08101	0.02112108141
<b>b</b> Optimization <sup>12*</sup>	7.9505248	2117.3376	221.19221	0.021386
Penski method (Excel software)	8.0005813	2146.4011	223.08102	0.02112108141
Standard deviation ( $\sigma$ ) <sup>†</sup>	0.0573171	33.9768	2.26229	NA

\*After conversion from Pa-K to Torr-°C units using eqs 4–6.

† From Penski method (Excel software).

Despite the small differences in the constants calculated from different methods for DEM, the vapor pressure values calculated from those constants are the same to five significant figures, as shown in Table 8. This should be expected because the differences in the solution values (excluding the constants from reference 12) are a small fraction of the estimated standard deviations; thus, all solutions are identical with respect to the error in the data.

It is worth noting that in his later report, Penski<sup>2</sup> calculated standard deviations for the **A** and **B** constants, assuming that the **C** constant was exact (as discussed in Section 4). Penski's calculations yielded values for  $\sigma_A$  and  $\sigma_B$  of 0.020955 and 3.200, respectively. These values severely underestimate the uncertainty, by a factor of almost 3 for **A** and by an order of magnitude for **B**, and show that there is dramatic impact if the error in **C** is ignored. In the remainder of this report, we present only the improved estimates of standard deviation, which were calculated using the methodology introduced in Section 4.

Table 8. Vapor Pressures (Torr, Equation 3) Calculated at Selected Temperatures for DEM Using Constants Listed in Table 7

Temperature (°C)	Penski <sup>2</sup>	<b>b</b> Optimization Method	Penski Method (Excel Software)
-40	0.00018915	0.00018915	0.00018915
0	0.023931	0.023931	0.023931
25	0.22313	0.22313	0.22313
50	1.3824	1.3824	1.3824
100	22.753	22.753	22.753
150	176.77	176.77	176.77
200	845.90	845.90	845.90

#### 5.4 VX

We recently recalculated the fit that we originally reported for VX (published in a 1999 ECBC technical report<sup>8</sup> and in the open literature<sup>9</sup> in 2012) using the Penski method (Excel software) and **b** optimization methods. In the published correlation, the nonstandard metric, *D*, which is the sum of the absolute values of the percent differences between the experimental and calculated values, was used in an effort to minimize the effect of experimental outliers. The *S* metric was used in both new calculations. The resulting fit constants are compared to the published values in Table 9. Both new fits produced essentially the same constants, with *S* values about 15% lower than the *S* values that were calculated using the published constants. Comparing the *S* metric found for the published fit to the other fits shown in Table 9 is not appropriate, however, because different metrics were used. The *S* value for the **b** optimization with the *D* metric is included here for information only. Table 9 also lists the standard deviations of the Antoine equation constants determined from the Penski method (Excel software) analysis.

Table 9. Antoine Constants (Equation 2), Standard Deviations, and  $S$  for VX

Method	<b>a</b>	<b>b</b>	<b>c</b>	$S$
<b>b</b> Optimization ( $D$ metric) <sup>8,9</sup>	23.725	6154.9	-60.165	0.748414
<b>b</b> Optimization ( $S$ metric)	23.274719	5839.6	-68.146215	0.6315428836
Penski method (Excel software)	23.274812	5839.6420	-68.145558	0.6315428780
Standard deviation ( $\sigma$ )*	0.365064	213.7409	5.124115	NA

\*From Penski method (Excel software).

Both new fits, which used the  $S$  metric, produced calculated values that are identical, as shown in Table 10. Differences compared to the original fit, also shown in Table 10, are within experimental error with the exception of the lowest value, which is well below the experimental temperature limit. The observed differences suggest a steeper dependence on temperature for the fits determined using the  $S$  metric and a more curved dependence, which is reflected in the greater absolute value of the **c** constants for the new fits.

Table 10. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for VX Using Constants Listed in Table 9 and Differences from Values Calculated Using the Penski Method (Excel Software)

Temperature (°C)	Penski Method (Excel Software)	<b>b</b> Optimization ( $S$ Metric)	<b>b</b> Optimization ( $D$ Metric) <sup>8,9</sup>	Percent Difference*
-40 <sup>†</sup>	0.0000054712	0.0000054714	0.0000070991	29.75
0	0.0054582	0.0054583	0.0056660	3.81
25	0.12070	0.12070	0.11794	-2.28
50	1.4545	1.4545	1.3785	-5.22
100	62.099	62.099	57.965	-6.66
150	920.87	920.87	870.14	-5.51
200	7017.1	7017.0	6778.8	-3.40

\*100·[**b** optimization ( $D$  metric) – Penski method (Excel value)]/Penski method (Excel value).

<sup>†</sup>Extrapolated; lower limit of experimental data was -13 °C.

## 5.5 RVX

We also recently recalculated our original correlation for RVX (published in a 2006 technical report<sup>10</sup> and in the open literature in 2012<sup>9</sup>) using the Penski method (Excel software) and **b** optimization methods. As with VX, in the published correlation, the nonstandard metric,  $D$ , was used, but the  $S$  metric was used in both new calculations in this work. In Table 11, the resulting fit constants are compared to the published values, and the standard deviations of the Antoine equation constants determined from the Penski method (Excel software) analysis are listed. Comparing the  $S$  metric found for the published fit to the other fits shown in Table 11 is not appropriate because the  $D$  metric was used. The  $S$  value for the **b** optimization with the  $D$  metric is included here for information only.

Table 11. Antoine Constants (Equation 2), Standard Deviations, and  $S$  for RVX

Method	<b>a</b>	<b>b</b>	<b>c</b>	$S$
Excel software ( $D$ metric) <sup>9,10</sup>	24.136	6464.0	-55.271	0.08878
<b>b</b> Optimization ( $S$ metric)	23.806112	6269.8	-59.493359	0.08515025789
Penski method (Excel software)	23.806171	6269.8357	-59.492558	0.08515025782
Standard deviation ( $\sigma$ )*	0.485769	297.1876	6.684891	NA

\*From Penski method (Excel software).

Values calculated at selected temperatures using the constants in Table 11 are listed in Table 12, which also shows the agreement between the new **b** optimization results and those generated using the Penski method (Excel software). All differences in calculated values are within the current experimental error limits, except for the lowest value, which was extrapolated well below the experimental temperature range.

Table 12. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for RVX Using Constants Listed in Table 11

Temperature (°C)	Penski Method (Excel Software)	<b>b</b> Optimization ( $S$ Metric)	<b>b</b> Optimization ( $D$ Metric)	Percent Difference*
-40 <sup>†</sup>	0.0000045588	0.0000045587	0.0000050138	9.98
0	0.0039301	0.0039301	0.0039587	0.73
25	0.085000	0.085000	0.083905	-1.29
50	1.0263	1.0263	1.0057	-2.00
100	45.456	45.456	44.756	-1.54
150	709.90	709.90	709.82	-0.01
200	5705.0	5705.0	5810.4	1.85

\*100·(**b** optimization ( $D$  metric) – Penski method (Excel value))/Penski method (Excel value).

<sup>†</sup>Extrapolated; lower limit of experimental data was -10 °C.

## 5.6 TDG

We recalculated our recently published TDG (CAS no. 111-48-8) correlation using the Penski method (Excel software) and the data as they appear in that report.<sup>3</sup> The resulting fit constants are close to the published values, obtained using the **b** optimization method with the  $S$  metric, as shown in Table 13. The differences between the published and new **b** optimization results are attributed to the difficulty associated with finding the best solution using the **b** optimization method. Table 13 also lists the standard deviations of the Antoine equation constants that were determined from the Penski method (Excel software) analysis.



Table 13. Antoine Constants (Equation 2), Standard Deviations, and  $S$  for TDG

Method	<b>a</b>	<b>b</b>	<b>c</b>	$S$
<b>b</b> Optimization ( $S$ metric) <sup>3</sup>	24.3482	6224.0	-67.9546	0.01235505437
<b>b</b> Optimization ( $S$ metric, this work)	24.348076	6223.9	-67.956992	0.01235504204
Penski method (Excel software)	24.348102	6223.9147	-67.956676	0.01235504202
Standard deviation ( $\sigma$ )*	0.411409	262.6135	6.323227	NA

\*From Penski method (Excel software).

These constants produced similar calculated values, several of which are listed in Table 14 with five significant digits to illustrate small differences. In each case, there are no differences between the new **b** optimization and the Penski method (Excel software) results, and the differences between those and the published correlation values are all less than 0.01%. The standard deviation estimates also indicate that all solutions are identical to within the error limits of the experimental data.

Table 14. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for TDG Using Constants Listed in Table 13

Temperature (°C)	Penski Method (Excel Software)	<b>b</b> Optimization ( $S$ Metric, This Work)	<b>b</b> Optimization ( $S$ Metric <sup>3</sup> )
-40	0.0000016275	0.0000016275	0.0000016276
0	0.0025191	0.0025191	0.0025191
25	0.067903	0.067903	0.067901
50	0.95991	0.95991	0.95987
100	52.183	52.183	52.180
150	921.03	921.03	920.99
200	8004.4	8004.4	8004.1

## 5.7 $N,N'$ -Diisopropylcarbodiimide (DICDI)

Our most recent report<sup>13</sup> details the vapor pressure of DICDI (CAS no. 693-13-0), which was determined using constants calculated via the **b** optimization method with the  $S$  metric. Recalculation of the correlation using the Penski method (Excel software) produced results (shown in Table 15) that reveal the fit described in reference 13 is nearly identical to the one obtained using the Penski method (Excel software). Table 15 also lists the standard deviations of the Antoine equation constants that were determined from the Penski method (Excel software) analysis.

Table 15. Antoine Constants (Equation 2), Standard Deviations, and  $S$  for DICDI

Method	<b>a</b>	<b>b</b>	<b>c</b>	$S$
<b>b</b> Optimization <sup>13</sup>	20.78393	3214.75	-73.96220	0.001117473101
Penski method (Excel software)	20.783935	3214.7534	-73.962050	0.001117473100
Standard deviation ( $\sigma$ )*	0.267660	142.8454	5.846359	NA

\*From Penski method (Excel software).

The vapor pressure values calculated using these constants are the same, to five digits, as those shown in Table 16. This result demonstrates again that the **b** optimization method can produce results comparable to those produced using the Penski method (Excel software), as long as the same metric is used and the **b** optimization method is reliable for the particular data set.

Table 16. Vapor Pressures (Pascal, Equation 2) Calculated at Selected Temperatures for DICDI Using Constants Listed in Table 15

Temperature (°C)	Penski Method (Excel Software)	<b>b</b> Optimization ( $S$ Metric) <sup>13</sup>
-40	1.8026	1.8026
0	104.03	104.03
25	629.16	629.16
50	2651.9	2651.9
100	22903	22903
150	106680	106680
200	337970	337970

Although the **b** optimization method and the Penski method (Excel software) can yield nearly identical results when the  $S$  metric is used, the former is more tedious and can give lower-quality fits in unfavorable cases. It is not clear to us whether those lower-quality fits are a result of the amount and quality of the data, the experience of the user, a combination of factors, or some other cause. It appears that the Penski method (Excel software) is consistently superior to the **b** optimization method because all data analyzed to date have yielded a smaller  $S$  when the Penski method was used.

We intend to use the Penski method (Excel software) with the  $S$  metric for future vapor pressure data correlations. Because viscosity data may also be correlated using the Antoine equation and similar procedures, it is likely that those correlations will also be improved by use of this method.

Table 17 lists the standard deviations of the Antoine constants from the tables in this report. The standard deviations for the three compounds studied by Penski and Latour were converted to enable direct comparisons. The table also includes the number of data points used for each analysis. It is clear from Table 17 that the compound with the greatest number of data points (DEM) had the smallest standard deviation for all three constants. When more data points

are available, the error is reduced due to the averaging inherent in the least-squares process. The mathematical dependence is easily seen: the standard deviations of **a**, **b**, and **c** depend on  $\sigma^2$ , which in turn is inversely proportional to the degrees of freedom. The number of data points is not the only consideration; their placement (where along the  $x$  axis they were measured), the validity of the assumption that the errors are identically and independently distributed, and of course, the validity of the underlying physical model (the Antoine equation) all have an impact. Therefore, it is not necessarily the case that a larger data set will result in lower standard deviations. VX is an example. Although VX has the second-largest number of data points of the data considered herein, its standard deviations were greater than those for several of the compounds with fewer data points. We attribute this observation to the fact that the very low vapor pressure of VX makes low-temperature data measurement very challenging, and the data is subject to more uncertainty than some of the other higher-volatility materials. Even though DICDI has the fewest data points, it has the second lowest  $\sigma_a$  and  $\sigma_b$  constants of the compounds discussed in this report, and the  $\sigma_c$  constant for DICDI is lower than that for all of the other compounds except DEM and VX. We attribute this observation to the unusually high precision of the DICDI experimental data.

Table 17. Standard Deviations of Antoine Constants for Compounds and Data in This Report

Compound	$\sigma_a$	$\sigma_b$	$\sigma_c$	Number of Data Points
1-Hexadecanol*	0.347819	254.9254	10.593177	13
1-Tetradecanol*	0.419529	241.4086	11.899260	12
DEM*	0.131978	78.2344	2.262292	66
VX	0.365064	213.7409	5.124115	41
RVX	0.485769	297.1876	6.684891	20
TDG	0.411396	262.6049	6.323022	11
DICDI	0.267660	142.8454	5.846359	7

\*Original analysis was done using eq 3 ( $\log(p)$ ); the original  $\sigma_a$  and  $\sigma_b$  values were multiplied by  $\ln(10)$  for comparison to the other entries in this table. The  $\sigma_c$  value is not affected by units change.

## 6. CONCLUSIONS

Several methods for correlating experimental vapor pressure data are explored in this report.

The method adopted by Penski and Latour<sup>5</sup> has been adapted for use with the commercial spreadsheet application Microsoft Excel with the Solver routine add-in, and it appears to produce high-quality solutions. The method is robust and efficient. We recommend it over the **b** optimization method.

As shown in this report, the **b** optimization method can find high-quality solutions under favorable conditions. However, this method is susceptible to finding unoptimized “solutions” unless the user is careful to avoid those that appear to be optimized but are not, due to poor choice of starting values for the **a** and **c** constants. As a result, the user must be able to determine when inappropriate starting values for the **a** and **c** constants are affecting the

optimization process. This can be done most easily by plotting the **c** versus *S* results in real time to ensure that a smooth curve is obtained. The **b** optimization method is tedious, requiring manual variation of the **b** constant while **a** and **c** are allowed to vary until a minimum *S* is determined.

The Antoine constants published previously for VX and RVX<sup>8-10</sup> are numerically different than those obtained using the Penski method (Excel software). The published fits were both based on the *D* optimization metric, and a direct comparison of Antoine constants to those determined using the *S* metric is not appropriate.

In this report, we also present a statistical analysis of the least-squares fitting of the Antoine equation. Penski had presented estimates for the standard deviations of the **a** and **b** parameters, but these were based on the erroneous assumption that the **c** coefficient was known exactly. We present updated equations derived from least-squares theory to more properly estimate the standard deviations of all three solution parameters. For DEM, we show that Penski's standard deviations underestimated the error by a factor of 3 in the case of the **a** parameter and by a factor of 10 in the case of the **b** parameter. Although we endorse Penski and Latour's method, we emphasize that their equations for the standard error<sup>5</sup> should be replaced by those discussed in this report.

Analysis of Antoine constants determined for the compounds and data in this report shows that the various methods generally succeed at finding the same effective solution. Differences in the solution values tend to be very small fractions of the standard deviations of the solution coefficients, and thus are effectively identical. The standard deviations of the solution parameters are also useful to compare the quality of different data sets.

## LITERATURE CITED

1. Thomson, G.W. The Antoine Equation for Vapor-Pressure Data. *Chem. Rev.* **1946**, 38, 1–39.
2. Penski, E.C. *Vapor Pressure Data Analysis Methodology, Statistics, and Applications*; CRDEC-TR-386; U.S. Army Chemical Research, Development, and Engineering Center: Aberdeen Proving Ground, MD, 1992; UNCLASSIFIED Report (ADA255090).
3. Brozena, A.; Tevault, D.E.; Irwin, K. Vapor Pressure of Thiodiglycol. *J. Chem. Eng. Data* **2014**, 59, 307–311.
4. Bauer, H.; Burschkies, K. Sättigungsdrucke einiger Senföle und Sulfide. *Chem. Ber.* **1935**, 68 (6), 1238–1243.
5. Penski, E.P.; Latour, Jr., L.J. *Conversational Computation Method for Fitting the Antoine Equation to Vapor-Pressure-Temperature Data*; EATR 4491; U.S. Army Chemical Research Laboratory: Edgewood Arsenal, Aberdeen Proving Ground, MD, 1971; UNCLASSIFIED Report (AD881829).
6. Seber, G.A.F.; Wild, C.J. *Nonlinear Regression*, John Wiley and Sons: Hoboken, NJ, 2003.
7. Tevault, D. *Vapor Pressure Data Analysis and Correlation Methodology for Data Spanning the Melting Point*; ECBC-CR-135; U.S. Army Edgewood Chemical Biological Center: Aberdeen Proving Ground, MD, 2013; UNCLASSIFIED Report (ADA592605).
8. Buchanan, J.H.; Butrow, A.B.; Abercrombie, P.L.; Buettner, L.C.; Tevault, D.E. *Vapor Pressure of VX*; ECBC-TR-068; U.S. Army Edgewood Chemical Biological Center: Aberdeen Proving Ground, MD, 1999; UNCLASSIFIED Report (ADA371297).
9. Tevault, D.E.; Brozena, A.; Buchanan, J.H.; Abercrombie-Thomas, P.L.; Buettner, L.C. Thermophysical Properties of VX and RVX. *J. Chem. Eng. Data* **2012**, 57, 1970–1977.
10. Buchanan, J.H.; Butrow, A.B.; Abercrombie, P.L.; Buettner, L.C.; Tevault, D.E. *Vapor Pressure of Russian VX*; ECBC-TR-480; U.S. Army Edgewood Chemical Biological Center: Aberdeen Proving Ground, MD, 2006; UNCLASSIFIED Report (ADA447993).
11. Kemme, H.R.; Kreps, S.I. Vapor Pressure of Primary n-Alkyl Chlorides and Alcohols. *J. Chem. Eng. Data* **1969**, 14, 98–102.
12. Brozena, A.; Buchanan, J.B.; Miles, Jr., R.W.; Williams, B.R.; Hulet, M.S. Vapor Pressure of Triethyl and Tri-n-Propyl Phosphates and Diethyl Malonate. *J. Chem. Eng. Data* **2014**, 59, 2649–2659.
13. Brozena, A.; Williams, B.R.; Tevault, D.E. *Vapor Pressure of N,N'-Diisopropylcarbodiimide*; ECBC-TR-1352; U.S. Army Edgewood Chemical Biological Center: Aberdeen Proving Ground, MD, 2006; UNCLASSIFIED Report.

Blank

## ACRONYMS AND ABBREVIATIONS

CAS	Chemical Abstracts Service
$C_{\text{sat}}$	saturation concentration
$\Delta H_{\text{vap}}$	enthalpy of vaporization
DEM	diethyl malonate
DICDI	<i>N,N'</i> -diisopropylcarbodiimide
DTA	differential thermal analysis
ECBC	U.S. Army Edgewood Chemical Biological Center
$P$	vapor pressure (Pa)
$p$	vapor pressure (Torr)
R	ideal gas constant
RVX	<i>O</i> -isobutyl- <i>S</i> -[2(diethylamino)ethyl] methylphosphonothiolate
$T$	absolute temperature (K)
$t$	temperature (°C)
TDG	thiodiglycol
VX	<i>O</i> -ethyl <i>S</i> -(2-diisopropylaminoethyl) methylphosphonothiolate

Blank



## APPENDIX

### SCREENSHOTS OF MICROSOFT EXCEL TEMPLATE

This appendix contains screenshots of the Microsoft Excel template used to calculate the Antoine (or Clausius–Clapeyron) fit for vapor pressure data using Penski’s method as described in this report. This template file, which performs all calculations discussed in this report, is available from the authors. The following narrative describes salient features of each slide. Data for *N,N'*-diisopropylcarbodiimide (DICDI) in Pascal-Kelvin unit format was used for demonstration purposes. The template can also perform the same analysis for data entered using Torr and degrees Celsius units.

Slides 1 and 2 show the compound identification and experimental data sections. The user enters the data as pressure and temperature pairs. The sums of the five highlighted parameters, identified as S1–S5 as in Penski and Latour’s report, are used to calculate Antoine constants and *S*, the metric that is used to assess fit quality. *S* is the sum of the squares of the differences of the logarithms of the experimental and calculated vapor pressure values. The Antoine constants are calculated by selecting an initial value for the *c* constant and allowing the Excel Solver program to minimize *S* by varying *c*. If an inappropriate initial *c* value is selected, it will be immediately obvious because the calculated values will not match the experimental data, demonstrating the robust quality of the updated Penski method. The four parameters,  $(c + T_i)^{-1}$ ,  $(c + T_i)^{-2}$ ,  $(c + T_i)^{-3}$ , and  $(c + T_i)^{-4}$ , and their sums shown to the right of S1–S5, are used to calculate standard deviations of the Antoine constants, as described in this report.

Slide 3 shows a list of calculated properties, including vapor pressure, volatility (or saturation concentration,  $C_{\text{sat}}$ ), and enthalpy of volatilization at selected temperature for the data entered into Slide 1. The last row contains the normal boiling point (i.e., at 1 atm), which was calculated using the derived Antoine constants and properties at the normal boiling point. Standard enthalpy of volatilization (enthalpy of vaporization for liquids and enthalpy of sublimation for solids) is the  $\Delta H_{\text{vap}}$  value at 25 °C. The entropy of vaporization is the ratio of enthalpy of vaporization at the normal boiling point to the temperature at the normal boiling point. These latter values are calculated and shown on Slide 1 when the template is used.

Slide 4 shows the statistical analysis that is described in detail in this report and performed automatically when the Excel template is used. The number of data points, *n*, is entered on Slide 1. The formulas used to calculate the values of the symmetric  $\Sigma$  matrix are shown at the upper right-hand side of the slide. The  $\hat{\sigma}^2$  value, also identified as  $(\sigma\text{-hat})^2$  is defined as  $S/(n-3)$ . Standard deviations of the constants are determined by taking the square roots of the products of the diagonal elements of the inverse matrix and  $\hat{\sigma}^2$ .

Slide 5 shows a standard plot of vapor pressure versus  $10000/T_K$  and the Antoine equation that is calculated when the template is used.

Slide 6 shows an optional feature incorporated into the template. Formula weight of the subject molecule is calculated by the Excel template when the user enters the number of each atom in that molecule. The formula weight is used to calculate volatility ( $C_{\text{sat}}$ ), shown on Slide 3.

	CALCULATION OF ANTOINE CONSTANTS				
	Compound:		DICDI		
Number of Data Points:			7		
	Molecular Weight:		126.2		
Normal Boiling Point:			148.06	°C	
			421.21	K	
	at 25 C	$\Delta H_{\text{vap}}$ :	47.28	kJ/mol	
	at nBPt	$\Delta S_{\text{vap}}$ :	93.4	J/mol-K	
Experimental Data					
Temperature			Pressure		
t/°C	T/K	10000/K	Torr		Pa
15.00	288.15	34.7041		2.42	323
55.46	328.61	30.4312		26.2	3490
65.45	338.60	29.5334		41.3	5500
77.06	350.21	28.5543		71.1	9480
87.9	361.05	27.6970		111.4	14860
111.15	384.30	26.0213		251.7	33560
148.27	421.42	23.7293		761.6	101530

Figure A-1. Slide 1.

		CALCULATION OF ANTOINE CONSTANTS								
		log P/torr = A - B/(C+t)								
						Rnd, 7			Ratio	
		$\sigma_a$	0.11384	A=	6.900169944	6.900170	a	20.7809985	0.9998569	
		$\sigma_b$	60.73921	B=	1395.460678	1395.461	b	3218.05973	1.00102224	
		$\sigma_c$	5.725408	C=	199.1242983	199.1243	c	-74.0257000	1.00087173	
				S=	0.00020232397					
		Calculations								
%Difference	Pcalc	S4/Y <sub>i</sub> log(P <sub>i</sub> )	S5/Y <sub>i</sub> <sup>2</sup>	S1/X <sub>i</sub> -1/(C+t)	S2/X <sub>i</sub> <sup>2</sup>	S3/X <sub>i</sub> Y <sub>i</sub>	(c + T <sub>i</sub> ) <sup>-1</sup>	(c + T <sub>i</sub> ) <sup>-2</sup>	(c + T <sub>i</sub> ) <sup>-3</sup>	(c + T <sub>i</sub> ) <sup>-4</sup>
0.27	2.416	0.38430	0.147686	-0.004670	0.00002181	-0.001795	0.004670	2.1811E-05	1.0186E-07	4.757E-10
-0.23	26.23	1.41782	2.010211	-0.003928	0.00001543	-0.005569	0.003928	1.5429E-05	6.0605E-08	2.3805E-10
-2.27	42.25	1.61582	2.610878	-0.003780	0.00001429	-0.006107	0.003780	1.4286E-05	5.3995E-08	2.0408E-10
1.03	70.39	1.85198	3.429835	-0.003621	0.00001311	-0.006706	0.003621	1.311E-05	4.7468E-08	1.7187E-10
2.01	109.2	2.04700	4.190216	-0.003484	0.00001214	-0.007132	0.003484	1.2138E-05	4.2291E-08	1.4734E-10
-0.40	252.7	2.40091	5.764357	-0.003223	0.00001039	-0.007738	0.003223	1.0387E-05	3.3478E-08	1.079E-10
-0.35	764.2	2.88170	8.304201	-0.002879	0.00000829	-0.008295	0.002879	8.2862E-06	2.3852E-08	6.8661E-11
	Σ	12.59953	26.45738	-0.025584	0.00009545	-0.043342	0.025584	9.545E-05	3.635E-07	1.414E-09

Figure A-2. Slide 2.

t	T	10000/T	VP <sub>calc</sub>		C <sub>sat</sub>	ΔH <sub>vap</sub>	
C	K	K <sup>-1</sup>	Pa	Torr	mg/m <sup>3</sup>	kJ/mol	kcal/mol
-40	233.15	42.891	1.801	0.01351	117.2	57.35	13.71
-30	243.15	41.127	5.943	0.04457	371.0	55.22	13.20
-20	253.15	39.502	17.16	0.1287	1029	53.36	12.75
-10	263.15	38.001	44.31	0.3324	2556	51.72	12.36
0	273.15	36.610	104.0	0.7802	5.780E+03	50.27	12.02
10	283.15	35.317	225.0	1.688	1.206E+04	48.98	11.71
20	293.15	34.112	453.6	3.403	2.349E+04	47.82	11.43
25	298.15	33.540	629.2	4.719	3.203E+04	47.28	11.30
30	303.15	32.987	860.3	6.453	4.308E+04	46.77	11.18
35	308.15	32.452	1161	8.706	5.717E+04	46.28	11.06
40	313.15	31.934	1547	11.60	7.496E+04	45.82	10.95
45	318.15	31.432	2036	15.27	9.716E+04	45.37	10.84
50	323.15	30.945	2652	19.89	1.246E+05	44.95	10.74
55	328.15	30.474	3418	25.64	1.581E+05	44.55	10.65
60	333.15	30.017	4363	32.72	1.988E+05	44.16	10.55
70	343.15	29.142	6916	51.88	3.059E+05	43.43	10.38
80	353.15	28.317	10608	79.57	4.559E+05	42.77	10.22
90	363.15	27.537	15797	118.5	6.602E+05	42.15	10.07
100	373.15	26.799	22904	171.8	9.317E+05	41.57	9.94
120	393.15	25.436	44905	336.8	1.734E+06	40.55	9.69
140	413.15	24.204	81316	609.9	2.987E+06	39.65	9.48
148.06	421.21	23.741	101325	760.0	3.651E+06	39.32	9.40

Figure A-3. Slide 3.

Calculate standard deviation of Antoine constants			
N =	7		
N-3 =	4		
$\Sigma = \begin{pmatrix} N & -\sum (T_i + c)^{-1} & \sum (T_i + c)^{-2} \\ b \sum (T_i + c)^{-2} & -b \sum (T_i + c)^{-3} & b^2 \sum (T_i + c)^{-4} \end{pmatrix}$			
( $\sigma$ -hat) <sup>2</sup>	5.058E-05	= S/(N-3)	
Matrix	7	-0.02558	1.332E-01
$\Sigma$	-0.02558	9.545E-05	-5.073E-04
	1.332E-01	-5.073E-04	2.753E-03
Inverse	256.21311	136221.2037	12707.939
$\Sigma^{-1}$	136221.2	72937512.12	6850915.61
	12707.939	6850915.614	648075.412
$\sigma_A$	0.1138399		
$\sigma_B$	60.73921		
$\sigma_C$	5.725408		
A	6.9001699		
B	1395.4607		
C	199.1243		

Matrix inverse calculation requires shift-ctrl-enter command after setting up 3x3 target matrix.

1. Select 3x3 target; touch = sign
2. Select matrix inverse function
3. Choose 3x3 sigma matrix to be inverted
4. Shift-ctrl-enter

Figure A-4. Slide 4.

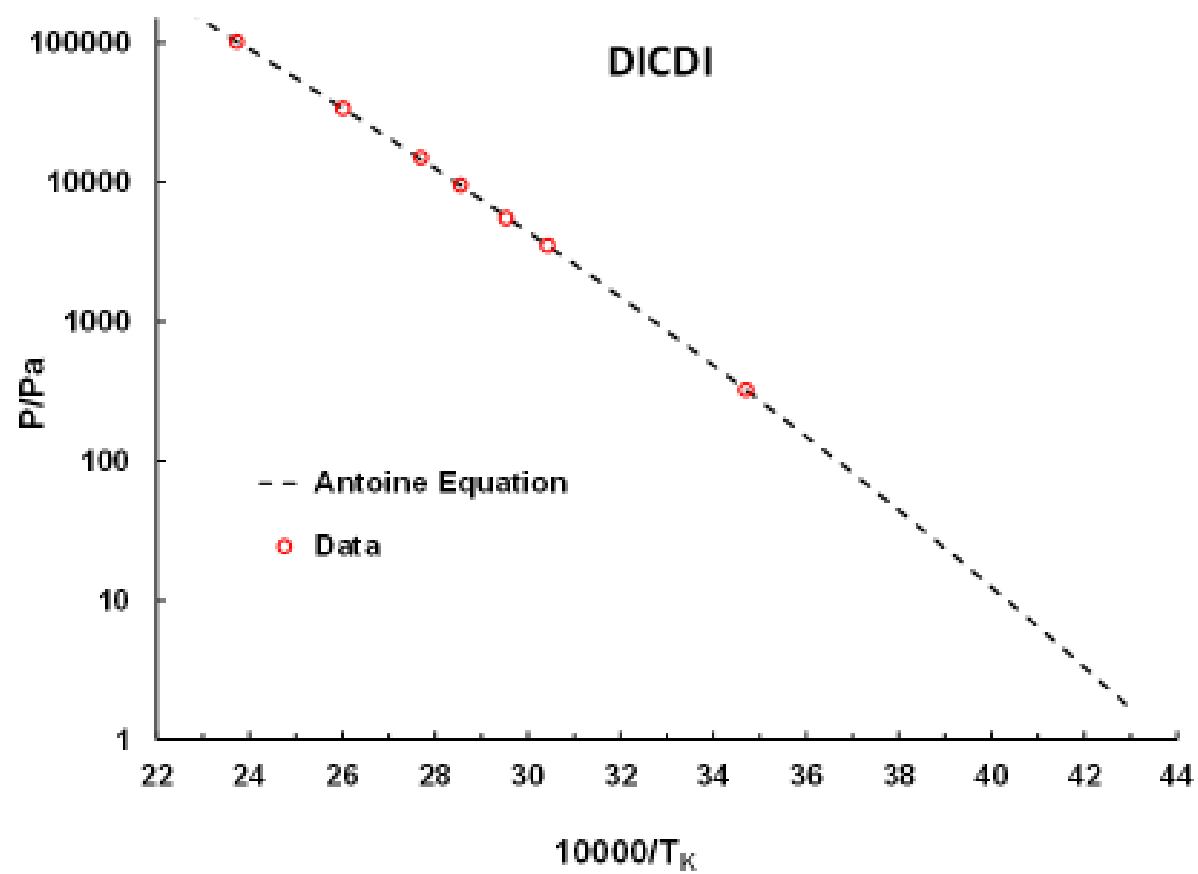


Figure A-5. Slide 5.

Calculation of Molecular Weight				
At No	Element	Std At Wt	Atoms	Subtotal
1	H	1.0079	14	14.1112
2	He	4.0026		
3	Li	6.9410		
4	Be	9.0120		
5	B	10.8110		
6	C	12.0107	7	84.0749
7	N	14.0067	2	28.0134
8	O	15.9994		
9	F	18.9984		
10	Ne	20.1797		
11	Na	22.9898		
12	Mg	24.3050		
13	Al	26.9815		
14	Si	28.0855		
15	P	30.9730		
16	S	32.0650		
17	Cl	35.4530		
Diisopropylcarbodiimide				
C <sub>7</sub> H <sub>14</sub> N <sub>2</sub>			MW	126.1995

Figure A-6. Slide 6.

Blank



## **DISTRIBUTION LIST**

The following individuals and organizations were provided with one Adobe portable document format (pdf) electronic version of this report:

U.S. Army Edgewood Chemical  
Biological Center (ECBC)  
RDCB-DRC-P  
ATTN: Brozena, A.  
Ellzy, M.

Defense Threat Reduction Agency  
J9-CBS  
ATTN: Peacock-Clark, S.  
Graziano, A.

Department of Homeland Security  
DHS-S&T-RDP-CSAC  
ATTN: Strang, P.  
RDCB-PI-CSAC  
ATTN: Negron, A.

G-3 History Office  
U.S. Army RDECOM  
ATTN: Smart, J.

Office of the Chief Counsel  
AMSRD-CC  
ATTN: Upchurch, V.

ECBC Rock Island  
RDCB-DES  
ATTN: Lee, K.

ECBC Technical Library  
RDCB-DRB-BL  
ATTN: Foppiano, S.  
Stein, J.

Defense Technical Information Center  
ATTN: DTIC OA

